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from Del Rio, Victoria, and Stephenville, facsimile charts, and rain data, 18 meteorological elements were developed for statistical analysis.

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ABSTRACT

Flash Flooding Events in South Central Texas. (August 1982)

Tom Wilson Utley, Jr., B.S., University of Utah

Chairman of Advisory Committee: Prof. Walter K. Henry

With the rapid increase in urban population and the intensification of agricultural pursuits there is an ever increasing demand for water in south central Texas. It is this demand which is the driving force behind the increase in rainfall enhancement programs in this region. The purpose of this research was to attempt to develop a forecast technique which would identify those days when meteorological conditions were favorable for flash flooding. Using this technique persons engaged in rainfall enhancement hopefully could avoid the potentially disastrous consequences of conducting rainfall enhancement operations in association with damaging rainfall, flooding, and loss of life.

This study examined 16 cases of flash flooding, reported in the National Oceanographic and Atmospheric Administration Storm Data publication, which occurred in the spring months of April through June for the 8-year period from 1973 through 1980. The area studied was bounded by the cities of Victoria, Del Rio, and Stephenville making a nearly equilateral triangle in south central Texas. A synoptic analysis indicated that all of the flooding events occurred with synoptic-scale convective rainfall activity and that rainfall was reported in the area for at least 48 hours prior to flooding. Synoptic analysis failed to verify a "frontal" model. With the use of rawinsonde data

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FLASH FLOODING EVENTS IN SOUTH CENTRAL TEXAS

A Thesis

by

TOM WILSON UTLEY, JR.

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

August 1982

Major Subject: Meteorology

ABSTRACT

Flash Flooding Events in South Central Texas. (August 1982)

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from Del Rio, Victoria, and Stephenville, facsimile charts, and rain data, 18 meteorological elements were developed for statistical analysis.

This analysis revealed a fair correlation between stability indices and moisture content indicators, and the potential for flash flooding. Decision logic tables were developed using linear regression equations in concert with rainfall information. When applied to the 8-year data base and to flash flooding events which occurred in 1981 they proved to be excellent predictors. When compared to the 1981 National Weather Service Quantitative Precipitation Forecast guidance they proved superior for operational use.

DEDICATION

To my Mother and Father who instilled in me the desire to learn.

To my Wife and Children who are my mainstay in life.

ACKNOWLEDGEMENTS

The writer's attendance of graduate school was sponsored by the United States Air Force through the auspices of the Air Force Institute of Technology and with the endorsement of Air Weather Service. To both of these the writer would like to express his gratitude.

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The writer would like to acknowledge the assistance provided by the following persons:

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a. General

The southeastern section of the Edwards Plateau in Texas has widely variable rainfall ranging from severe drought conditions to equally devastating flash floods. The isohyets shown in Fig. 1 indicate an increase in rainfall to the north and west of the Balcones Escarpment. The headwaters of several rivers are located in this area as is the Edwards Aquifer (see Fig. 2). The climatological evidence of increased rainfall in this area, coupled with the rapid increase in urban population and the intensification of agricultural pursuits makes this region a prime target for rainfall enhancement operations.

b. Objectives

Any attempt to provide assistance to those engaged in weather modification must address times when cloud seeding should not be attempted. The two most obvious sub-categories in this domain are: (1) times when the atmosphere is so devoid of moisture that no amount of seeding would produce significant precipitation, and (2) those times when conditions indicate the potential for damaging rainfall and flash flooding. In the latter case the potentially calamatious consequences of conducting rainfall enhancement activities in association

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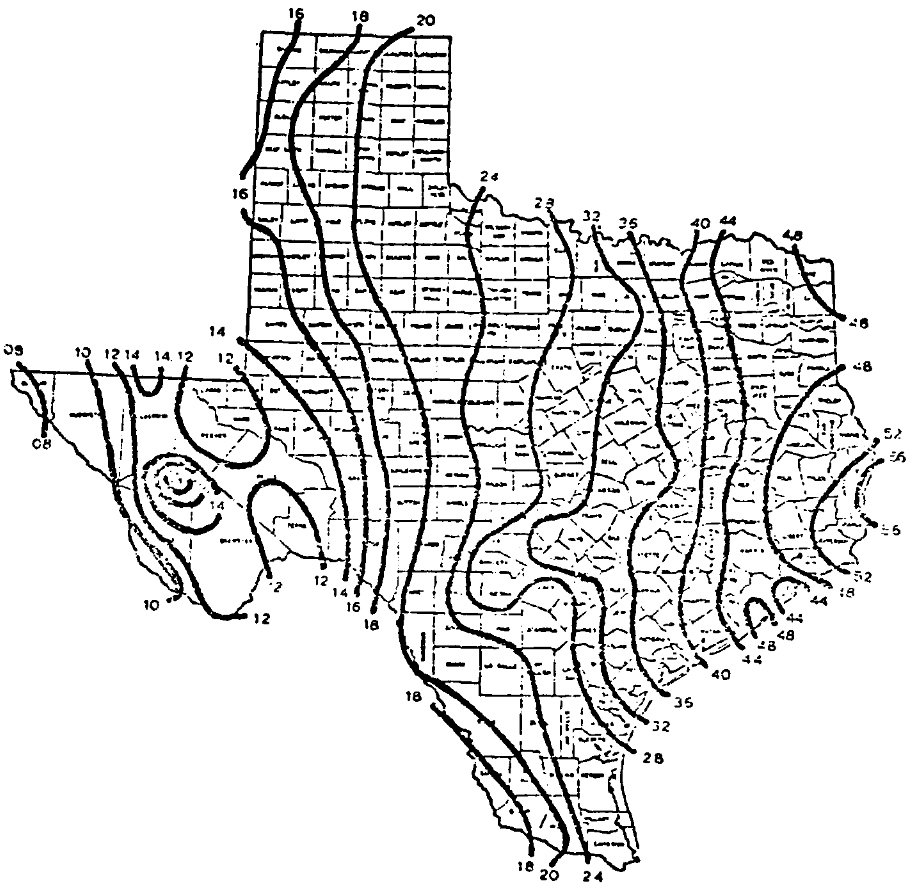

Fig. 1. Isohyets of total precipitation based on the period 1931-1960. (From Griffiths and Orton, 1968).

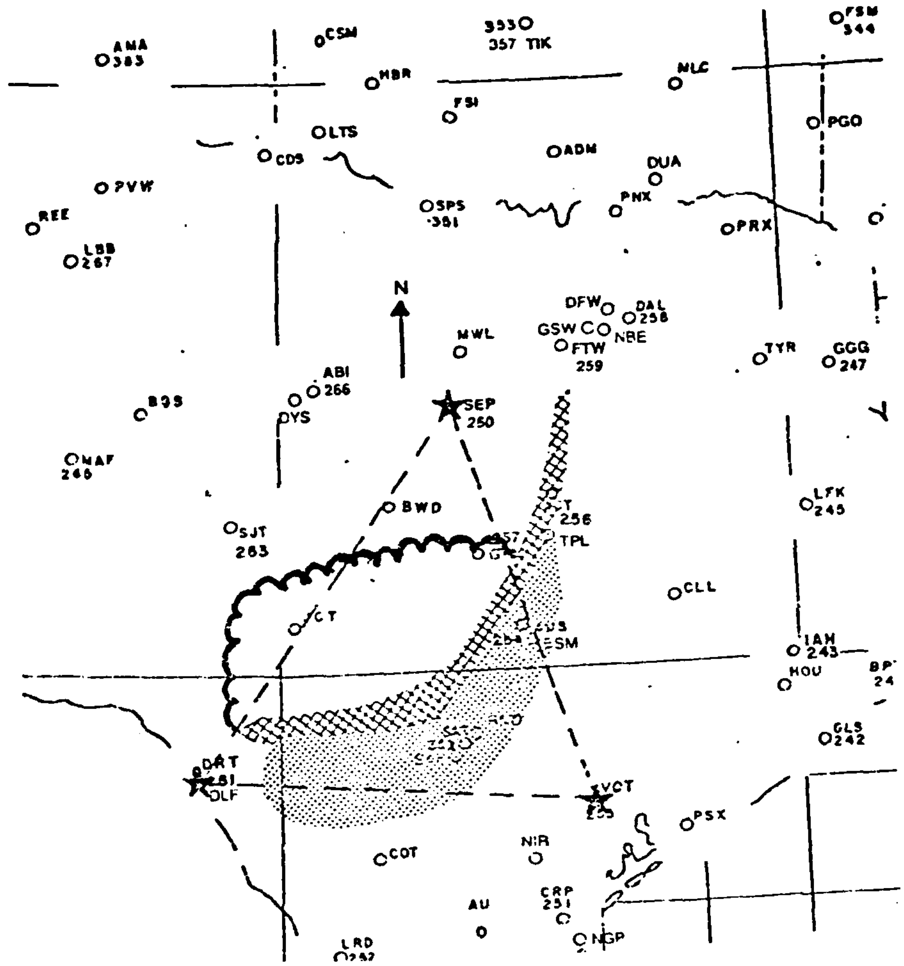

Fig. 2. Location of Balcones Escarpment and the Edwards Aquifer . The indicates the northern extent of the drainage area of the aquifer. The three starts locate the three rawinsonde stations - Victoria, Stephenville, and Del Rio. (From Henry, 1981).

with damaging rainfall, flooding, property loss, and loss of life is obvious. The objective of this research is to develop operational criteria to forecast potential flash flood conditions.

c. The geographical area

The area is within a triangle with a rawinsonde station at each vertex. The triangle is almost equilateral with each side approximately 400 km (see Fig. 3). Figure 3 also depicts the terrain, which is near sea level at the southeast corner and rises to a height of 900 m along the westernmost leg. Figures 4, 5, and 6 show the smoothed terrain along each leg of the triangle.

Details of the area are in Tables 1, 2, and 3.

d. *Previous work*

This research is a continuation of a precipitation study conducted by Henry (1981). The objective of the Henry study was to examine upper air conditions over the southeast portion of the Edwards Plateau in Texas, and to determine which conditions correlated most closely to the occurrence of rainfall. Henry used a modified Bellamy (1949) technique and data from three rawinsonde stations to compute a variety of meteorological elements (vorticity, convergence, vertical motion, etc.) over an 8-year period (1973-1980). Although the study produced useable guidelines for predicting periods when conditions were too dry for cost-effective cloud seeding operations, more extensive study is required to provide useable predictands for the cases where cloud seeding operations

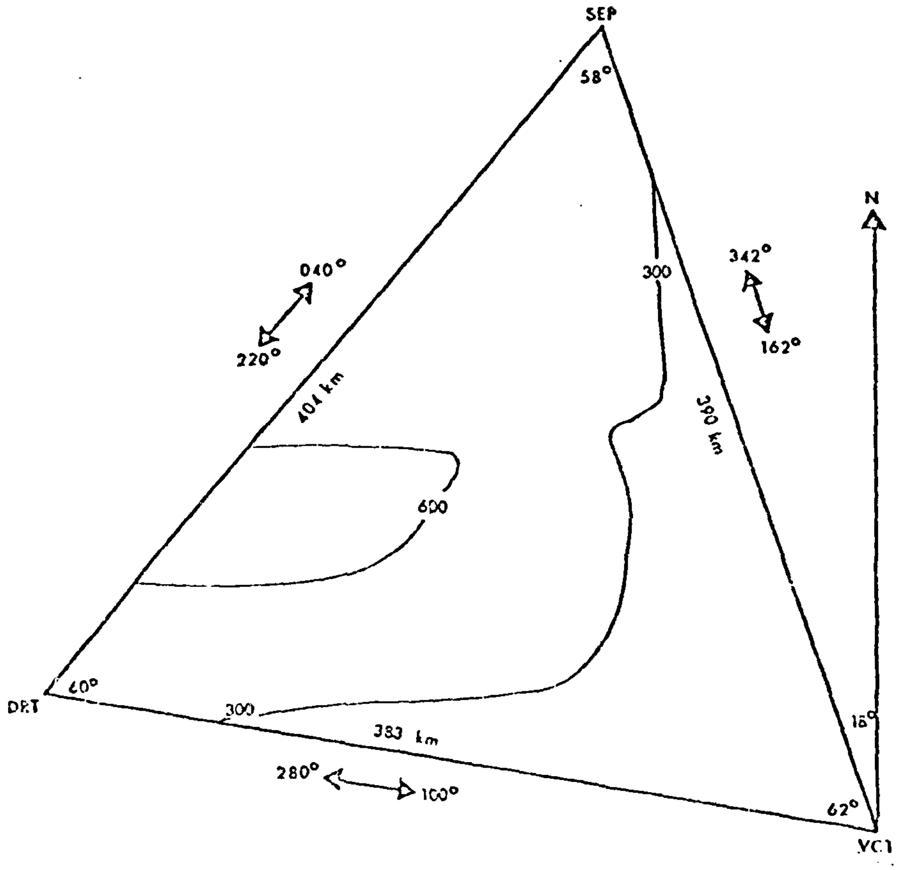

Fig. 3. The triangle formed by Del Rio, Stephenville, and Victoria, and the generalized terrain. Lengths shown are in kilometers and azimuth is from true North. (From Henry, 1981).

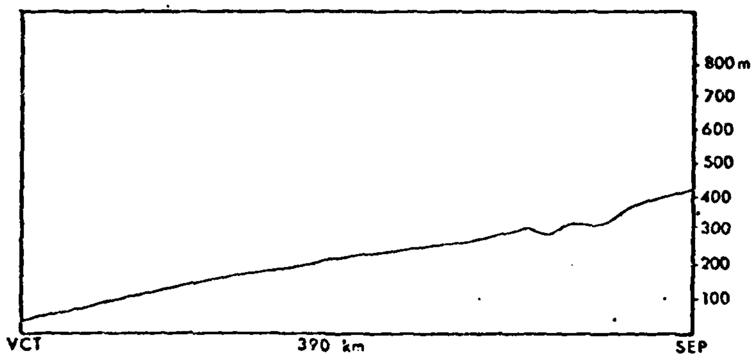

Fig. 4. Terrain along the Victoria-Stephenville side of the triangle. Heights in meters. (From Henry, 1981).

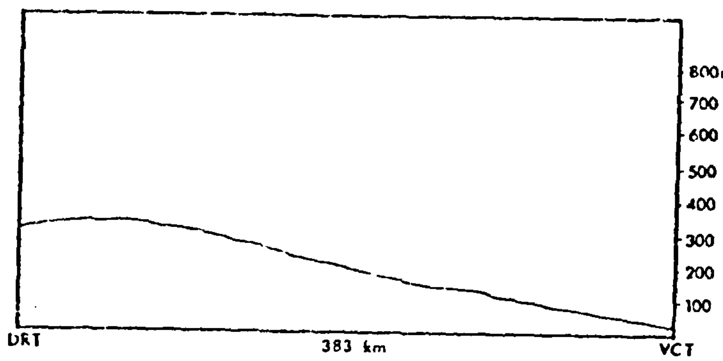

Fig. 5. Terrain along the Del Rio-Victoria side of the triangle. Heights in meters. (From Henry, 1981).

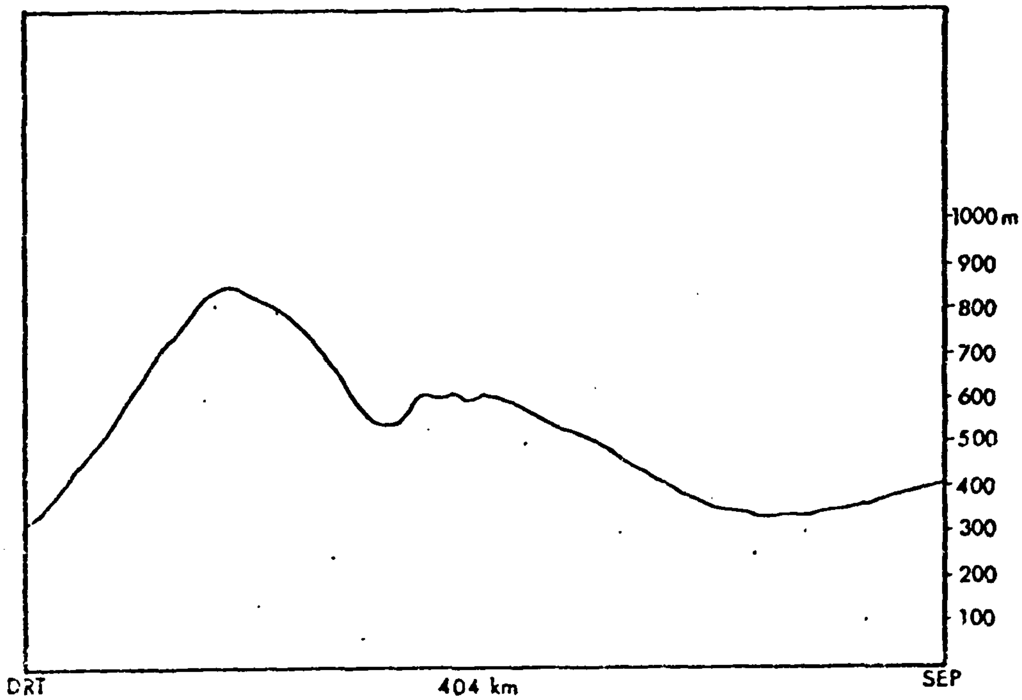

Fig. 6. Terrain along the Del Rio-Stephenville side of the triangle. Heights in meters. (From Henry, 1981).

TABLE 1. Station information for Del Rio, Stephenville, and Victoria (from Henry, 1981).

Station Name	Station Number	Call Letters	Elevation (m)	Latitude	Longitude
Del Rio	72261	DRT	313	29°22'N	100°55'W
Stephenville	72260	SEP	398	32°13'N	98°11'W
Victoria	72255	VCT	36	28°51'N	96°55'W

The locations and elevations listed changed from year to year, but for uniformality these values will be used.

TABLE 2. Description of triangle, length and orientation of side (from Henry, 1981).

Stations	Distance km	Heading
DRT-VCT	383	280° or 100°
DRT-SEP	404	220° or 040°
SEP-VCT	390	342° or 162°

Area 66551 km^2
Average elevation 289 m
Average terrain slope N-S from center south leg toward the north is 1:350.

TABLE 3. The cross-section along the legs of the triangular study area as shown in Figures 4, 5, and 6 (from Henry, 1981).

	DRT-VCT	DRT-SEP	SEP-VCT
Average surface elevation, m	197	525	215
Area of air, surface to 1500 m, m^2	499,049,000	393,900,000	500,955,000
Average height of air, surface to 1500 m, m	849	1012	858
Average pressure, surface to 1500 m in St. Atmos. mb	914	897	918
Average temperature, surface to 1500 m in Std. Atmos. T°C	9.5	8.4	9.5
In standard atmosphere ρ kg m^{-3}	1.124	1.108	1.130
When T_v is 20°C ρ kg m^{-3}	1.086	1.069	1.091

should be curtailed due to the possibility of potentially damaging rainfall.

There has been extensive research over the past several years on the subject of flash flooding. In May 1978 and again in March 1980 the American Meteorological Society hosted conferences on flash floods. At the first conference Maddox and Chappel (1978) presented a paper describing the meteorological aspects of 20 significant flash flood events. The purpose of their study was to identify specific large-scale patterns associated with intense precipitation, and to isolate mesoscale features responsible for these events. The study consisted of flooding cases which occurred during 1975 and 1976 in the United States. The study included synoptic and stability indices analysis and produced a set of criteria common to all events studied. Events were "typed" as Meso High, Frontal, Western, East Slope, and Synoptic.

Maddox, Chappel, and Hoxit (1979) later completed a study of 150 intense convective precipitation events which occurred from 1973 to 1977. The events were classified according to four basic types and a detailed description of the mesoscale environment was given.

The synoptic environment of flash flood storms was studied by Knowles and Jehn (1975), Huff (1978), and Chin and Hansen (1980). Knowles' work stressed the use of synoptic climatology to forecast precipitation events over central Texas. The Huff study examined 16 storms which produced flash flooding in Illinois during the period 1949-1968. The storms were divided into two categories based on aerial extent with a small to medium group having areas of 6,500 km^2 or less, while the large group consisted of storms encompassing areas

6,500 to approximately 20,000 km^2. Storms were then "typed" in a fashion similar to the procedures used by Maddox and Chappel. Low- and mid-level winds, moisture, stability, and antecedent rainfall conditions were included in the synoptic analyses. The study concluded that flash flood storms developed most frequently in an mT airmass in a nonfrontal environment. Chin and Hansen conducted a synoptic analysis of the devastating floods which occurred in Texas in August of 1978 due to tropical storm Amelia. Changnon and Vogel (1980) studied localized, small-scale, and intensive warm season rainstorms. Their studies indicated a strong bias toward nocturnal activity. Korty (1980) conducted an analysis of mesoscale systems that produced flash flooding in east Texas and the lower Mississippi Valley. In addition to confirming many of the general conclusions of other researchers, he found that weak, mid-level shortwaves were an influencing mechanism. He cited the inability of current numerical models to effectively predict system intensification, the lack of nighttime observations, and the absence of definitive low-level convergence as major obstacles to accurate prediction.

Although substantial research has been conducted on flash flooding, few of the conclusions are directly applicable to this study. In general, synoptic analysis conducted by previous researchers was for the period during, or within a few hours of the event's occurrence rather than 12 to 36 h prior to the event as was the case in this study. Studies conducted in significantly different geographical areas and studies grouping storms from a wide variety of geographical locations also had limited applicability. Obvious variations in

topography weather regimes, time-of-year, and storm type limited the validity of all but the most general conclusions.

2. Data

a. Flash flooding events

An examination of National Oceanographic and Atmospheric Administration Storm Data publications for the years 1973 through 1980 revealed two distinct maxima of flash flooding events. One period from April through June and another from August through October. As there was strong evidence that the flooding during these periods was caused by distinctly different atmospheric processes and, as the April through June period produced a significantly greater amount of events, it was selected for study. Sixteen cases of flash flooding were studied (see Table 4).

b. Rawinsonde data

Rawinsonde reports from Victoria, Del Rio, and Stephenville for the times 0000 GMT and 1200 GMT were extracted from 35 mm film records of the Northern Hemisphere Data Tabulations published by the National Climatic Center (NCC) for the years 1973 through 1978 inclusive. At the time of this study the 1979 and 1980 data were not available from the NCC and were obtained from the archives of the Department of Meteorology at Texas A&M University. In 1973 the rawinsonde station, then located in Fort Worth, Texas, moved to Stephenville. This change of location required an elevation correction to standardize the data. Missing data were supplied when possible through the use of the NOAA Climatological Data publication and archived teletype and facsimile

TABLE 4. List of dates and locations of flash flooding events within Victoria, Stephenville, and Del Rio triangle. Storm days during the period April through June, 1973-1980.

#	DATE	COUNTY	TIME (GMT)
1.	15 April 73	Bexar	2300
2.	7 May 75	Bell	2300
3.	10 June 75	Bastrop, Caldwell, Travis	0120
4.	6 May 76	Bell	0100
5.	13 April 77	Comal	2140
6.	15 April 77	Kerr	0510
7.	9 May 77	Bell	2310
8.	10 April 78	Bexar	0700
9.	7 June 78	Bexar	0000
10.	1 June 79	Bell	1800
11.	5 June 79	Bell	1400
12.	19 April 79	Caldwell, Guadalupe, Kerr, Kendall	0240
13.	21 April 79	Bexar	0515
14.	13 May 80	Bell, Bexar, Travis, Burnet	1800
15.	15 May 80	Lampasas, Bell	1400
16.	21 June 80	Comal	1200

data.

c. Rainfall data

Rainfall data were taken from the "Climate Summaries, Texas". During the 8-year period a total of 80 stations reported. During any one month, however, only about 70 stations reported. These were reports of total daily rainfall and were taken once each day at approximately 7:00 a.m. local time. Care was taken in the selection of reporting stations to insure a fairly uniform areal distribution.

d. Facsimile data

National Meteorological Center facsimile charts were available from the Department of Meteorology archives. Surface, 850, 700, and 500 mb charts were the primary charts used in the analysis; however, the Radar Summary, the four panel limited fine mesh (LFM) baroclinic charts of 500 mb heights and vorticity, and the four panel charts with Lifted Index, K Index, precipitable water, freezing level and average relative humidity surface to 500 mb also were used.

3. Data Development

After a study of elements examined in previous research efforts, eighteen elements were selected for this study (see Table 5).

a. Elements obtained directly from facsimile products included:

Lifted index (LI), K index (KI), precipitable water (PH_2O), and mean relative humidity surface to 500 mb (RHSFC500) were read directly from National Weather Service facsimile charts for each of the three stations and an average was used.

b. Elements obtained directly from rawinsonde data

Several elements were taken directly from the three rawinsonde stations and averaged. The elements derived in this manner were: surface pressure, temperature and relative humidity, height of the 850 mb surface and temperature, height of the 700 mb surface and the 700 mb temperature, height of the 500 mb surface and 500 mb temperature (T500), the 500 mb relative humidity and relative humidity at the freezing level (RHFL). The elements followed by a contraction were used directly in the analysis. The other elements were used to calculate advection, vorticity, and vertical motion.

c. Total Totals Index

The Total Totals Index (TTI) was computed for each rawinsonde station using the following formula:

TABLE 5. Meteorological elements used to determine the state of the atmosphere prior to flash flooding events over South Central Texas in a triangular area bounded by the cities of Del Rio, Stephenville, and Victoria.

Element and contraction used in this study	Units
1. LI - Lifted Index	none
2. KI - K Index	none
3. PH_2O - Precipitable Water	in.
4. RHSFC500 - Relative Humidity Surface at 500 mb	%
5. T500 - Temperature at 500 mb	°C
6. TTI - Total Totals Index	none
7. VM850 - Vertical Motion at 850 mb	m s^{-1}
8. VM700 - Vertical Motion at 700 mb	m s^{-1}
9. VM500 - Vertical Motion at 500 mb	m s^{-1}
10. VORT850 - Vorticity at 850 mb	s^{-1}
11. VORT700 - Vorticity at 700 mb	s^{-1}
12. VORT500 - Vorticity at 500 mb	s^{-1}
13. $ADVH_2O$ - Moisture advected into the area from the surface to 500 mb	g s^{-1}
14. DVH_2O - Moisture flux through the wall between Del Rio and Victoria from the surface to 850 mb	g s^{-1}
15. DVWND - Low Level Wind DRT to VCT	m s^{-1}
16. RHFL - Relative Humidity at the Freezing Level	%
17. PCNTRN - Percent of Stations Reporting Rain	%
18. AREARN - Average Rainfall	in.

$$TTI = (T850 + TD850) - (2(T500)) \quad (1)$$

where T850 is the temperature at 850 mb, TD850 is the 850 mb dewpoint, and T500 is the 500 mb temperature. All values were in °C. Once the TTI was computed for each station an average was taken to represent the area.

d. Convergence, vertical motion, vorticity, and moisture advection

Convergence, vertical motion, vorticity, and moisture advection were derived using a modified Bellamy (1949) technique. Details of the procedure are provided in Appendix A.

e. Precipitation data

The average areal precipitation values (AREARN) were obtained by totaling the amount of precipitation reported in each 24-h period and dividing by the number of stations reporting. Percentage of stations reporting rain (PCNTRN) was the percent of the total number of stations reporting which reported precipitation. The stations were uniformly distributed over the area by initial selection.

4. Analysis

a. Case selection and synoptic analysis

A review of the National Oceanographic and Atmospheric Administration Storm Data publication was made for the months April through June for the years 1973 through 1980 inclusive. Sixteen cases of flash flooding, occurring in the drainage basin of the Edwards Aquifer, were selected for case study (see Table 4). They were very nearly evenly divided by month of occurrence with six occurring in April and five in both May and June. Annual distribution was also somewhat evenly distributed with one event reported in 1973, two in 1975, one in 1976, three in 1977, two in 1978, four in 1979, and three in 1980. There were no reported cases in 1974. With the notable exceptions of Bell and Bexar Counties, the flash flooding events showed fairly even geographical distribution.

Bell County had seven events and Bexar County reported five while Caldwell, Comal, Kerr, and Travis Counties each had two events. Bastrop, Burnet, Guadalupe, Kendall, and Lampasas Counties reported one event each (see Fig. 7). Diurnal distribution of the occurrence of flash flooding events was evenly distributed with the only time periods not experiencing an event being between 0800 and 1200 GMT, and from 1600 until 1800 GMT (see Fig. 8). A synoptic analysis was accomplished for four levels: surface, 850 mb, 700 mb, and 500 mb, and for three time periods: 12, 24, and 36 h prior to the flash flooding events. The National Weather Service analysis was used both to insure against the investigator introducing a bias, and because it

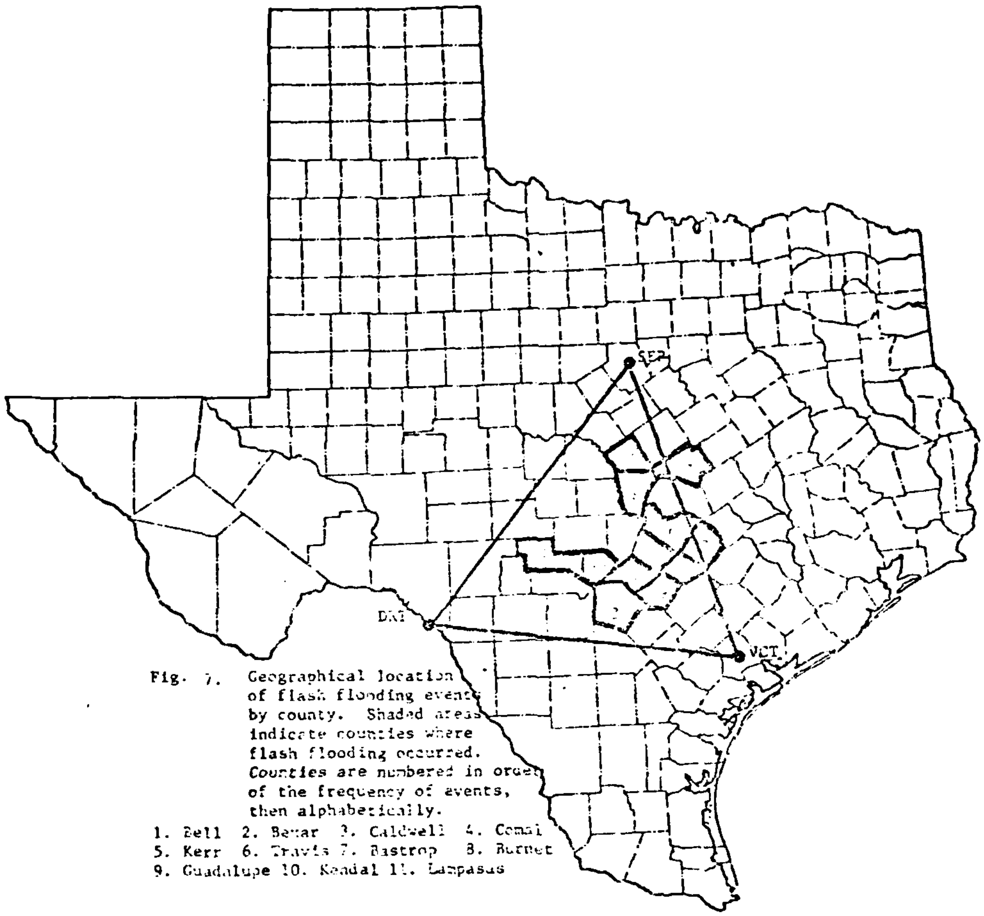

Fig. 7. Geographical location of flash flooding events by county. Shaded areas indicate counties where flash flooding occurred. Counties are numbered in order of the frequency of events, then alphabetically.
1. Bell 2. Bexar 3. Caldwell 4. Comal
5. Kerr 6. Travis 7. Bastrop 8. Burnet
9. Guadalupe 10. Kendal 11. Lampasas

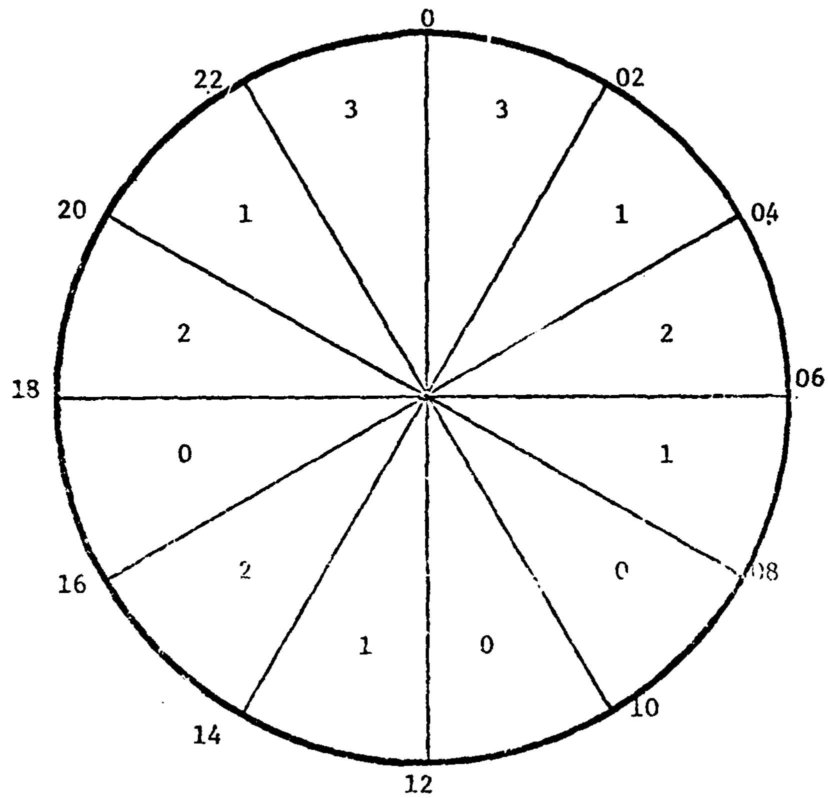

Fig. 8. Diurnal distribution of flash flooding events (GMT). Number of floods in 2 h periods.

was felt that the charts would be an integral part of any forecast technique which evolved from this study and the user should not be required to reanalyze charts prior to implementing the technique.

Personal observation of flash flooding events in this area and a preliminary analysis of the data led to the hypothesis of a frontal model for flash flooding. The flooding events were hypothesized to be associated with synoptic scale rainfall triggered by a northwest-southeast oriented cold front. The front should enter the northwestern portion of the state and move steadily southeastward through the study area. Ahead of the frontal system would be moist southeasterly flow from the surface through 700 mb with increasing upward vertical motion throughout the period. It soon became apparent that the frontal model would not verify. Only five of the cases studied had a frontal system in the area within 12 h of the occurrence of flooding. With a frontal system entering Texas every three or four days during the spring months April through June the chances of a flash flood being associated with a frontal system were no better than the overall probability of a frontal system being in the area. An analysis of the five cases with frontal systems also dispelled the models favored orientation and movement of the front. Of the five fronts only two were active cold fronts. The remaining three were stationary (see Fig. 9).

A synoptic analysis of each event was conducted at four levels: surface, 850 mb, 700 mb, and 500 mb, and for three time periods: 12 h, 24 h, and 36 h prior to the occurrence of flash flooding. The analysis included frontal systems, pressure centers, surface pressures, pressure

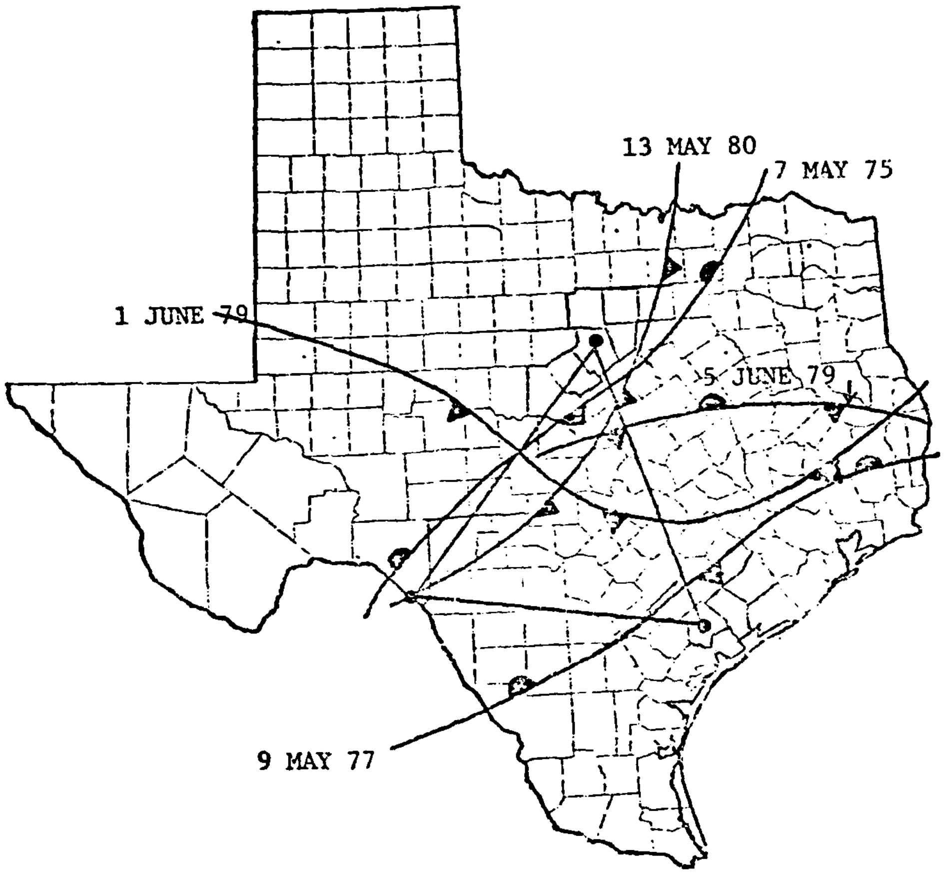

Fig. 9. Frontal systems associated with flash flooding events. Of the sixteen cases studied only five had a frontal system in the study area within 12 h of the flooding event.

heights, and winds at each level. The analysis failed to provide support for the model as height and pressure patterns and wind speed and direction changes occurred in an apparently random fashion.

An analysis of radar facsimile charts and the data on the percent of stations reporting rainfall during a flood event provided strong evidence that each flood event was a result of convective rainfall and occurred within a synoptic scale rainfall area. The percent of stations reporting rainfall ranged from 50 to 98.8%. An analysis of antecedent rainfall conditions provided useful information. For 48 h prior to each flooding event rainfall was reported and, with only one exception, the rainfall occurring in the period 24 h prior to the event was greater than that reported 48 h prior to the event (see Table 6). The average area rainfall reported during the 24-h period when flash flooding occurred ranged from 0.207 to 1.175 in.

b. Statistical analysis

A statistical analysis of stability indices, moisture convergence, vertical motion, and vorticity was conducted (see Table 5 for a list of elements). The first phase of the analysis was to study the sign and magnitude of the various elements at 12, 24, and 36 h prior to the flooding events. Results of this phase of the analysis were disappointing. The stability indices and moisture content indicators showed a fair correlation and reasonable values; however, the dynamic elements, vorticity, convergence, and vertical motion, exhibited erratic sign and magnitude fluctuations. After failing to

TABLE 6. Antecedent rainfall conditions. Twenty four hour average areal rainfall over the study area 24 h and 48 h prior to each studied flooding event.

#	Date	Rain 24 h Prior (in)	Rain 48 h Prior (in)
1.	15 April 73	.634	.121
2.	7 May 75	.177	.093
3.	9 June 75	.247	.057
4.	5 May 76	.270	.005
5.	13 April 77	.112	.001
6.	14 April 77	.573	.112
7.	9 May 77	.043	.006
8.	10 April 78	.021	.001
9.	6 June 78	.197	.001
10.	18 April 79	.393	.313
11.	20 April 79	.414	.336
12.	1 June 79	.794	.206
13.	5 June 79	.316	.306
14.	13 May 80	.322	.101
15.	15 May 80	.600	.750
16.	21 June 80	.319	.020

achieve useful results, an analysis of the change in the elements with time as they neared the flood event was conducted. The results were inconclusive. The stability indices and moisture content indicators provided more realistic results than did the dynamic elements.

Next the 18 elements were examined, using a variety of statistical analysis computer programs, in an attempt to determine how the elements related to each other and how they related to average areal rainfall. Again moisture indicators and stability indices showed much better correlation than the dynamic elements. However, when the equations were applied to the 8-year data base they consistently "over forecast" significant rainfall events and occasionally failed to accurately forecast a flood event. In an attempt to identify the cause of the forecast error the most promising elements were plotted using average areal rainfall as the dependent variable (see Fig. 10 for an example). After analyzing the plots, the reason for the consistent "over forecasting" of significant rainfall events became apparent. Throughout the range of independent variables there was a substantial number of days without significant rainfall and the majority of these days was being forecast as having sufficient rainfall to produce flash flooding. Several techniques were attempted to improve the results of the forecast equations. Each element was plotted and manually examined to find the most promising elements and to find the most beneficial limits. A variety of data bases were tried in an attempt to isolate flooding potential days. Several iterations provided equations with slightly improved reliability; however, the tendency to forecast flooding conditions for a large number of dry days remained a formidable obstacle to the effectiveness of the equations.

STATISTICAL ANALYSIS SYSTEM

Plot of Rain*L Index Legend: A=1 Obs, B=2 Obs, etc

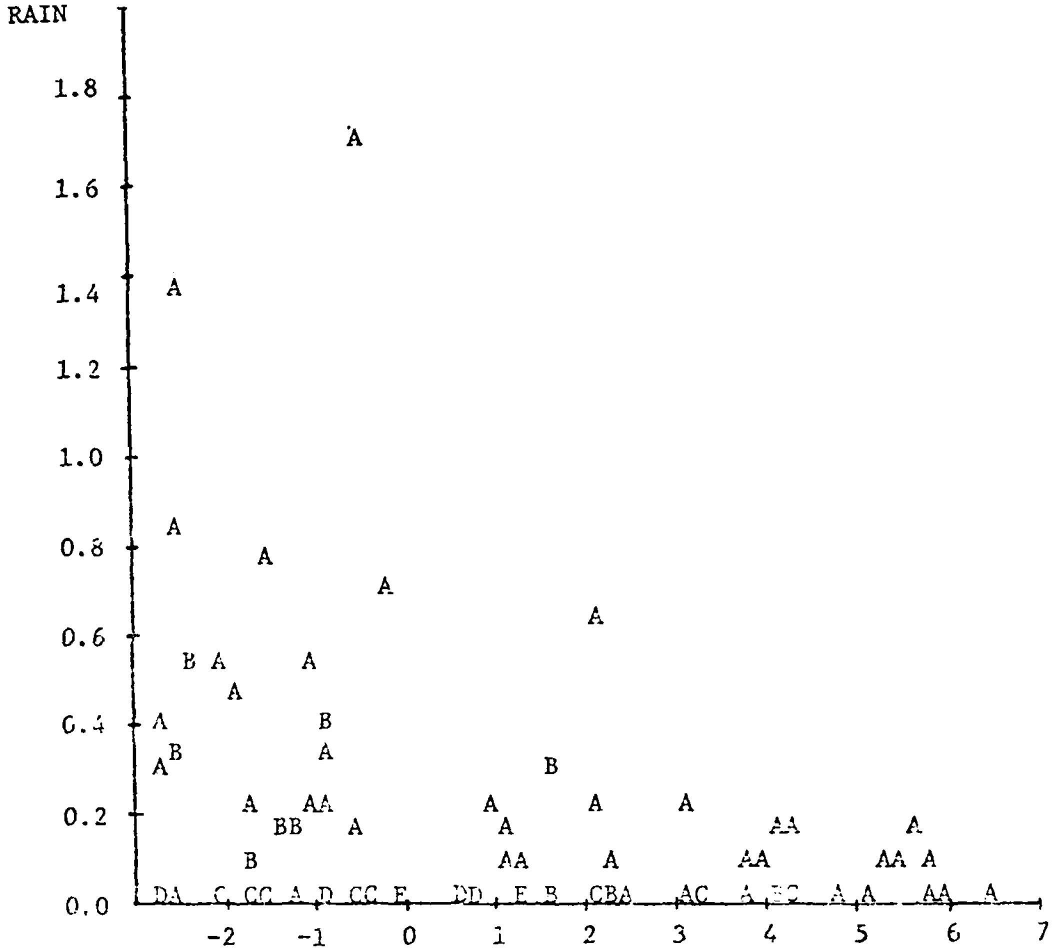

Fig. 10. Plot of L Index against average areal rainfall.

5. Results and Conclusions

a. Development of forecasting technique

The breakthrough in achieving a useful forecasting technique came with the combining of regression equations developed during the analysis phase with the antecedent rainfall data.

Using a data base originating with days when average areal rainfall equalled or exceeded 0.2 in, equations to predict flash flooding potential at 12, 24, and 36 h prior to the event, for each month, were obtained (see Tables 7 through 9). The range of the individual elements was fixed by visual inspection of the plotted data to insure that all potential flood events were included. Conveniently, all the elements used in the equations can either be obtained directly from National Weather Service facsimile charts or, as in the case of the total totals index, easily calculated from data obtained from the charts.

The forecast technique is designed for use with 1200 GMT data as follows:

1) Calculate average areal rainfall for the previous 24-h period.
2) Select logic tables corresponding to forecast period and month.
3) Determine current values, from facsimile charts, of the elements used in the tables.
4) If any one of the elements is outside the ranges specified in the selected table forecast no flash flood potential for that period.

Table 7. Forecast decision table for April. Separate equations, elements and ranges for 12, 24 and 36 h periods.

12 h Forecast	Ranges	
Element	Min	Max
LI	No lower bound	4.8
PH2O	0.70	No upper bound
RHSFC500	36.0	No upper bound
TOT	35.0	No upper bound

Equation: Fcst = -1.87 + 0.016 (LI) + 0.001345 (PH2O) + 0.0154 (RHSFC500) + 0.035 (TOT).

24 h Forecast	Ranges	
Element	Min	Max
LI	No lower bound	6.5
PH2O	0.74	No upper bound
RHSFC500	36.0	No upper bound
TOT	40.5	No upper bound

Equation: Fcst = 0.723 - 0.052 (LI) - 1.35 (PH2O) + 0.21 (RHSFC500) + 0.002144 (TOT).

36 h Forecast	Ranges	
Element	Min	Max
LI	No lower bound	4.8
PH2O	0.69	No upper bound
RHSFC500	33.0	No upper bound
TOT	34.8	No upper bound

Equation: Fcst = -0.065 - 0.05 (LI) = 1.14 (PH2O) + 0.0224 (RHSFC500) + 0.0142 (TOT).

Table 8. Forecast decision table for May. Separate equation, elements and ranges for 12, 24 and 36 h periods.

12 h Forecast	Ranges	
Element	Min	Max
KI	13.25	No upper bound
PH2O	.82	No upper bound
TOT	42.5	No upper bound

Equation: $Fcst = 0.049 + 0.0012\ (KI) + 0.0112\ (PH2O) + 0.009\ (TOT)$.

24 h Forecast	Ranges	
Element	Min	Max
LI	No lower bound	3.8
KI	10.0	No upper bound
PH2O	0.8	No upper bound
TOT	41.7	No upper bound

Equation: $Fcst = 0.83 - 0.02\ (LI) + 0.013\ (KI) - 0.3\ (PH2O) - 0.0043\ (TOT)$.

36 h Forecast	Ranges	
Element	Min	Max
LI	No lower bound	0.5
PH2O	0.7	No upper bound
TOT	37.3	No upper bound

Equation: $Fcst = 0.761 - 0.03\ (LI) - 0.2\ (PH2O) - 0.002\ (TOT)$.

Table 9. Forecast decision table for June. Separate equations, elements and ranges for 12, 24 and 36 h periods.

12 h Forecast	Ranges	
Element	Min	Max
KI	19.0	No upper bound
PH20	1.2	No upper bound
RHSFC500	46.5	No upper bound
Equation: Fcst = -0.235 + 0.023 (KI) - 0.011 (PH20) + 0.002 (RHSFC500).		
24 h Forecast	**Ranges**	
Element	Min	Max
KI	18.2	No upper bound
PH20	1.2	No upper bound
RHSFC500	49.0	No upper bound
Equation: Fcst = -0.92 + 0.005 (KI) + 0.71 (PH20) + 0.004 (RHSFC500).		
36 h Forecast	**Ranges**	
Element	Min	Max
KI	17.2	No upper bound
PH20	1.2	No upper bound
RHSFC500	44.6	No upper bound
Equation: Fcst = 0.520 + 0.012 (KI) - 0.185 (PH20) + 0.011 (RHSFC500).		

5) Examine the average areal rainfall for the preceeding 24 h and the average areal rainfall for the period from 24 to 48 h prior. If either report is 0.00 in forecast no flood potential for 12 and 24 h. If the average areal rainfall for the past 24 h is 0.00 in forecast no flood potential prior to 36 h.

6) If all elements fall within the specified ranges of the table and the antecedent rainfall conditions of 5) above do not eliminate flood potential, use the current values of the appropriate elements in the 12-, 24-, and 36-h forecast equations. If an equation yields a result less than 0.2 in forecast no flash flooding potential for that period. If the equation yields a result greater than 0.2 in proceed to 7).

7) (1) If both the 24- and 48-h antecedent rainfall amounts are greater than 0.50 in forecast flash flooding potential by the end of the forecast period.

(2) If the antecedent rainfall amounts show an increase over the past 48 h, forecast flash flooding potential by the end of the forecast period.

(3) If the antecedent rainfall amounts show a decrease over the past 48 h, forecast no flash flood potential for the forecast period.

In the 16 flash flood cases studied an average areal rainfall of 0.2 in was the least amount reported for the 24-h period in which flooding occurred. This value was therefore used as a lower bound for

forecasting flash flood potential.

b. Validation of technique tested against 8-year data base

When tested against the 8-year data base the technique showed promising results. Forecasts were verified in the following manner:

1) If a forecast for flood potential was made and the reported average areal rainfall was equal to or greater than 0.2 in the forecast was counted as valid.
2) If a forecast of no flood potential was made and areal rainfall was less than 0.2 in the forecast was counted as correct.
3) If a forecast of no flash flood potential was made due to an antecedent rainfall of 0.00 being reported (see Para. 5.a.5) and 0.2 in or more areal rainfall was reported but no flooding occurred the forecast was counted as correct.
4) If a forecast of no flash flood potential was made for any reason other than a zero rainfall antecedent condition and more than 0.2 in of areal rainfall was reported the forecast was considered incorrect.
5) If a forecast of flood potential was made and less than 0.2 in of areal rainfall was reported the forecast was considered incorrect.

Using this technique every instance of actual flooding was accurately forecast; however, the technique continued to over forecast flood potential. A large part of the error was the result of the technique forecasting flooding 24 to 36 h prior to its occurrence.

Although this characteristic reduces skill score it is a highly desirable trait in that it provides adequate lead time for persons engaged in weather modification programs. A 12-, 24-, and 36-h forecast was made for each day of the 8-year data base.

Using a straight percentage of correct forecasts versus the total number of forecasts made, the technique yielded a high of 89.7% for the June 12-h forecast, and a low of 70% for the May 36-h forecast. Using a skill score equation, defined in Fig. 11, the results ranged from a low of 0.387 for the May 36-h forecast to a high of 0.727 for the June 12-h forecast.

b. Verification of technique against 1981 floods (independent data)

Three flooding events which occurred in Spring 1981 were used as a realtime test for the technique. The technique results were then compared with the National Weather Service Quantitative Potential Rainfall Forecast (QPF) guidance.

The first of the three cases selected occurred on the evening of the 22nd of April and the morning of the 23rd. High winds, damaging hail, heavy rains, and flash flooding swept across Texas from Del Rio to Beaumont.

By using the appropriate facsimile charts and available rainfall data, a table of required values was contracted (see Table 10).

Accuracy Matrix

Forecast

Occurred		Yes	No
	Yes	a	b
	No	c	d

a = number of times flash flooding potential rainfall amount was forecast and occurred.

b = number of times flash flooding potential rainfall amount was forecast not to occur but occurred.

c = number of times flash flooding potential rainfall amount was forecast and did not occur.

d = number of times flash flooding potential rainfall amount was forecast not to occur and did not occur.

Skill Score Equation

$$SS = \frac{F - R}{T - R}$$

where F = (a + d) = total number of correct forecasts.

T = (a + b + c + d) = total number of forecasts.

$R = \frac{(a + b)(a + c) + (c + d)(b + d)}{T}$ = number of times correct forecast could have been made as a result of random chance.

Fig. 11. Technique for determining skill score of flash flood forecasting technique when applied to the 8-year data base.

Table 10. Data calculated for forecast technique test of April 1981 flooding events.

	DATE					
Element	19	20	21	22	23	24
LI		2	0	-2	1	7.3
PH2O		0.7	0.8	1.1	1.1	0.9
RHSFC500		32	41	53	57	60
TTI		40	43	45	43	42
AREARN	0.127	0.058	0.148	0.385	1.300	0.128

Beginning the test on the morning of the 20th, all variables were within the range prescribed in Table 7, and since neither the average areal rainfall amount on the 19th or the 20th was 0.00 in the values of the elements were used in the 12-, 24-, and 36-h forecast equations. The 12-h equation yielded a result of 0.056 in; therefore, as the value was less than 0.2 in a forecast of no flash flood potential for the next 12 h was made. The 24-h forecast equation yielded a value of 0.486 in which would indicate a significant rainfall; however, the antecedent rainfall conditions for the 19th and 20th revealed a decrease in amount of areal rainfall, therefore the forecast of 24 h was for no flash flood potential. The 36-h forecast followed the 12-h pattern and no flash flood potential was forecast for 36 h.

The next forecast was made on the morning of the 21st. Again all elements fell within the prescribed ranges and this time all three

equations yielded results greater than 0.2 in. The antecedent rainfall conditions, then under consideration, were those of the 20th and the 21st. As neither of the two was 0.00 in and the 48-h tendency showed an increase in rainfall amount, a forecast for potential flash flooding was made for all three time categories.

The forecasts for the morning of the 23rd and the 24th also satisfied all the conditions for a forecast of flash flooding potential for all three time categories.

Forecasts of flash flood potential ended on the morning of the 24th. Although all elements remained within the prescribed ranges and all three equations resulted in a forecast of greater than 0.2 in of rainfall, the sharp decline in reported rainfall amount called for a forecast of no flood potential to be issued. Figure 12 illustrates the forecasting technique result compared to actual flooding and to QPF guidance.

Date/Time (GMT)	20/1200	21/1200	22/1200	23/1200	24/1200	25/1200
Forecast		T---∞∞∞	∞∞∞∞∞∞	∞∞∞∞∞∞		
Actual Flooding			xxx	xx		
QPF	——			—		

T = time technique first indicated flood potential

Lead Time = -------

Forecast = ∞∞∞∞∞∞

Actual Flooding = xxxxxxx

QPF = ————

Fig. 12. Forecast technique results compared to actual flooding and QPF guidance for the April 1981 case using 1200 GMT data.

In this case the technique provides excellent decision assistance to the user engaged in weather modification and is superior to QPF guidance. The 21/1200 GMT 12-h forecast indicated flash flooding potential by the end of the period as did the 24-h and 36-h forecasts. Significant rainfall in the area preceeded flooding by three to four hours. Flooding began at 23/0800 GMT and was last reported at 23/1730 GMT. The flash flood forecasting technique began forecasting flood potential slightly more than 24 h in advance of the occurrence of flooding. In practice this would be ideal lead time for those engaged in weather modification. The technique continued to forecast flood potential until the 24/1200 GMT forecast or approximately 12 h after flooding had ended. Here the extended period clearly assists the weather modifier who has no wish to have the operation associated with the flash flood event.

QPF guidance suggested flash flood potential for a 12-h period ending 24 h prior to the time when flooding began, and again for a 6-h period from 23/1800 GMT to 24/0000 GMT beginning 30 minutes after flooding had ended.

The second and third cases tested occurred on 25 and 29 May 1981. These events were the product of two separate atmospheric systems. The first event was by far the worst causing 13 deaths and injuring 100 persons in the city of Austin, Texas. Using the same procedure as in the previous test case a data table was developed for the period 21 through 31 May 1981 (see Table 11).

The first forecast was made for 22 May. All elements were within assigned ranges; however, on the 21st no rainfall was reported.

Table 11. Data used to apply the flash flood forecasting technique to the flooding events of May 24 and 29, 1981.

	Date										
Element	21	22	23	24	25	26	27	28	29	30	31
LI		-1	-6	-6	4	1	-4	-5	-6	0	2
KI		4	10	25	28	21	3.3	4.7	22.3	31	27.3
PH O		1.0	1.3	1.2	1.3	1.0	1.0	1.0	1.3	1.4	1.3
TTI		49	52	56	45	44	49	53	48	49	47
AREARN	0.000	0.003	0.029	0.687	0.666	0.004	0.000	0.010	0.186	0.355	0.320

Therefore a forecast of no flood potential was made for the 12- and 24-h periods. The 36-h equation yielded a forecast rainfall value of .431 in and as the antecedent conditions indicated increasing amounts of rainfall; a forecast for flash flooding potential in 36 h was made.

On the 23rd and 24th all elements remained within the prescribed ranges, all equations forecast significant rainfall, and the antecedent conditions indicated an increase in rainfall amount; therefore a forecast for flash flooding potential was made for all periods.

On the 25th the elements remained within the prescribed ranges and all equations indicated significant rainfall; however, the antecedent rainfall showed a slight decrease from the 24th to the 25th. Normally this would indicate a forecast of no flash flood potential; however, as both values exceeded 0.5 in, using the rule stated in paragraph 5.a.7, a forecast for flash flooding potential was made. The morning of the 26th all elements remained within the limits and all equations again indicated significant rainfall; however, with the sharp decline in antecedent rainfall amount over the past 48 h a forecast of no significant rainfall for all three periods was made.

On the 27th KI exceeded the prescribed range for the 12- and 24-h periods, therefore a forecast of no flash flood potential was made. The 36-h forecast equation indicated significant rainfall, however, the most recent antecedent rainfall amount was 0.00 in and a forecast of no flash flood potential was made. KI continued to exceed the range on the 28th, and the 12- and 24-h forecasts were once again for no flash flood potential. The 36-h forecast equation again indicated significant rainfall and an increase in antecedent conditions caused a forecast for

flash flood potential to be made. On the 29th and 30th a forecast for flash flooding potential was made for all periods.

A slight drop in antecedent rainfall conditions on the morning of the 31st caused a forecast of no flash flooding potential to be made for all periods.

Figure 13 compares the forecast technique results with actual flooding and QPF guidance. The 36-h forecast made using 22/1200 GMT data indicated an areal rainfall of 0.431 in by 24/0000 GMT which was well above the flash flood lower bound of 0.2 in. Actual flooding began at 24/0500 GMT; therefore, the technique provided a 36-h warning and actually came within five hours of predicting the onset of flooding.

	21	22	23	24	25	26	27	28	29	30	31
Forecast		T-	-----	∞∞∞	∞∞∞	∞∞		T-	---∞∞	∞∞∞	∞∞
Actual				XXX	XXX				XX	XX	
QPF				——	——					——	—

T = time forecast technique first indicated flood potential

Lead Time = -------

Forecast = ∞∞∞∞∞

Actual = xxxxxxx

QPF = ———

Fig. 13. Forecast technique results compared to actual flooding and QPF guidance for May 1981 flooding events.

The forecast periods are 12-h increments. Flooding continued to be reported until 25/1300 GMT; however, the forecast technique called for a flooding forecast until 26/1300 GMT. QPF guidance issued near

24/1200 GMT, seven hours after flooding had begun, indicated the probability of flooding for the next 24 h. Flooding continued to be reported for at least one hour beyond the QPF guidance.

The 36-h forecast issued near 28/1200 GMT provided early warning of the second flood event. The technique continued to forecast flood potential until 31/1200 GMT. Flooding began at 29/1700 GMT and continued until 30/2000 GMT. QPF guidance issued near 30/1200 GMT forecast flash flooding potential for a 24-h period ending at 31/1200 GMT. Again, as with the first storm, QPF guidance indicated flooding potential after flooding had begun.

In the three test cases the forecasting technique was superior to QPF guidance and should prove useful to a variety of customers interested in flash flood events. Prior to its implementation, however, a procedure for obtaining average areal rainfall on a real-time basis must be developed. As all studied flooding events were associated with synoptic scale convective activity, a technique of estimating rainfall amounts using radar reports should be appropriate. The area is covered by radars at Hondo and Stephenville, Texas.

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APPENDIX A

Details of the computation of convergence, vertical motion, vorticity and moisture advection.

A modified version of the Bellamy (1949) technique was utilized. The first step in computing convergence in the area was to obtain a wind component normal to each leg of the triangle (see Figures A1 and A2).

Steps in Computing Normal Wind Component:

(1) Compute u + v vectors at points A, B, C, and D.

Equation used:

u = wind speed x sin (360° - wind direction)

v = wind speed x cos (360° - wind direction)

(2) Add u components at A and B and take average for $\bar{u}$. Add v components in the same order for $\bar{v}$. Repeat process for u and v components at C and D.

(3) Add $\bar{u}$ component over DRT to $\bar{u}$ component over SEP and take the average for $\bar{\bar{u}}$. Repeat the process for $\bar{\bar{v}}$.

(4) Normalize $\bar{\bar{u}}$ and $\bar{\bar{v}}$ to triangle wall and add them together for normal wind $\bar{w}$.

Equation used:

$\bar{w} = \bar{\bar{u}}$ x sin (wind direction - wall orientation)

+ $\bar{\bar{v}}$ x sin (wind direction - wall orientation).

The wind direction for $\bar{\bar{u}}$ will always be 270°, and the wind direction for $\bar{\bar{v}}$ will always be 360°.

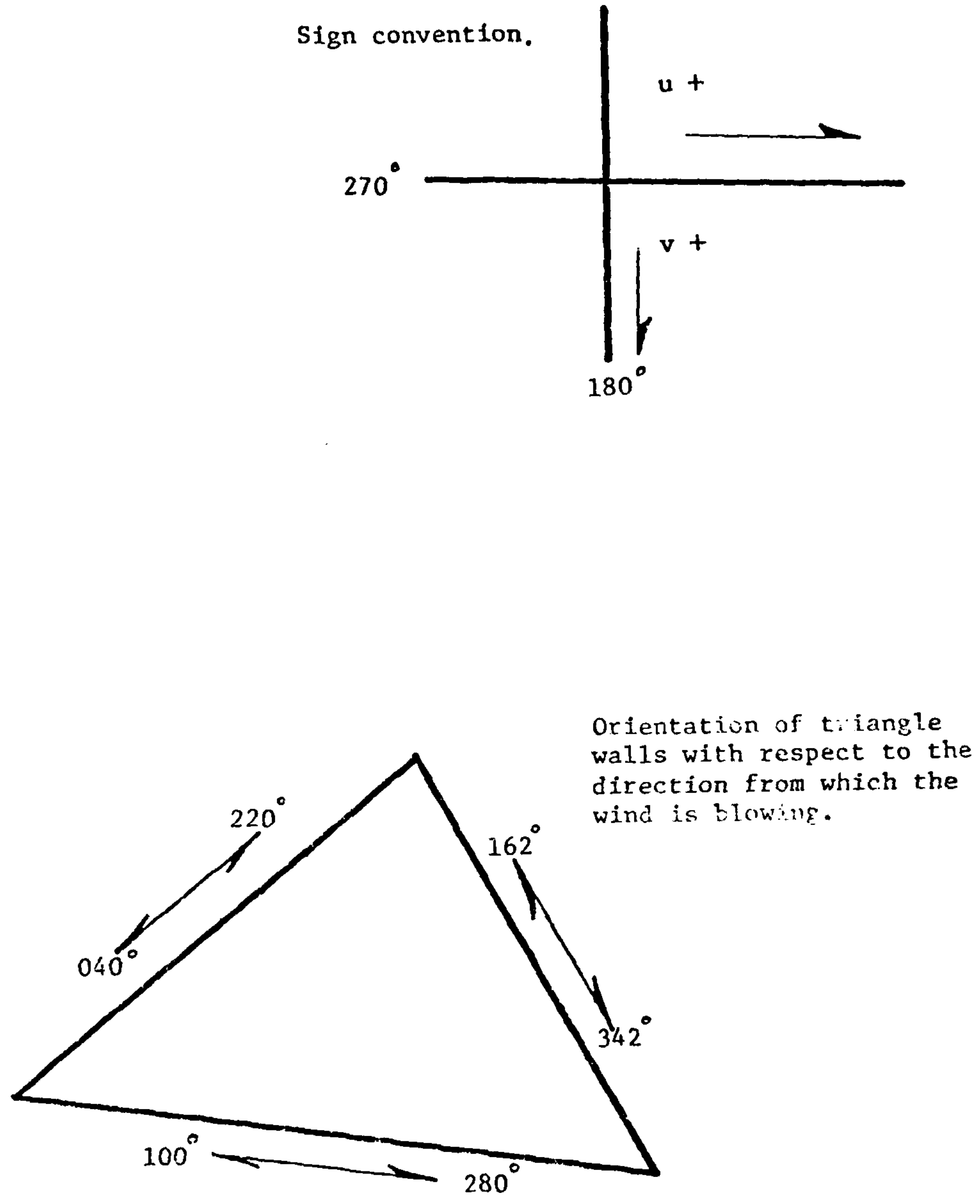


Fig. A1. Sign convention and orientation of the sides of the triangle used to calculate Convergence, Vorticity and Advection useing a modified Bellamy technique.

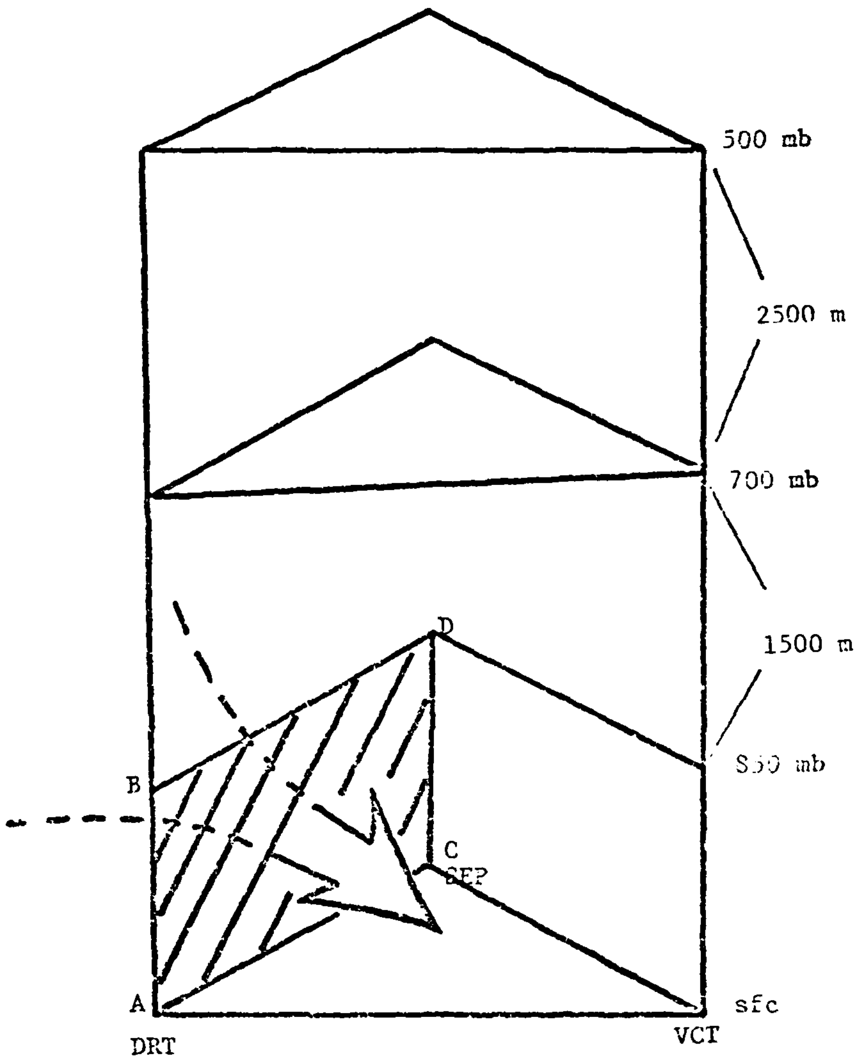


Fig. A2. Normal wind component through the DRT-SEP wall surface to 850 mb.

The surface to 850 mb wind component normal to the wall between Del Rio and Victoria (DVWND) was used as a separate element in the analysis.

The next step in computing convergence was to repeat the above process to obtain a normal wind component for the other two walls of the triangle. The volume of air through each wall was then obtained by multiplying each normal wind vector by the area of the respective triangle wall. A one second time step was used thus producing the volume of air passing through the wall in one second. Changes in terrain were considered in this calculation (see Table 1 through 3 and Figures 4 through 6 for determination of these areas).

Adding the three volumes thus obtained provided the convergence in the triangle from the surface to 850 mb. The same procedure was used to calculate the volume of air between 850 mb and 700 mb. At this level the area of each wall was calculated by multiplying the distance between the stations by 1500 m. A distance of 1500 m represents an average thickness from 850 mb to 700 mb for the area at this time of year. To calculate convergence at this level the convergence from the layer below was included.

$$C_2 = V_1 + V_2 + V_3 + C_1$$

where C_2 is the convergence in the layer from 850 mb to 700 mb, V_1, V_2 and V_3 represents the volumes of air transported through the three walls of the triangle in this layer, and C_1 is the surface to 850 mb convergence.

Convergence in the 700 mb to 500 mb layer was calculated using the same procedure and adding C_2 to the sum of the volumes. Areas at this

level were obtained by multiplying the distance between the stations by 2500 m. Again this is a calculated average thickness for the level.

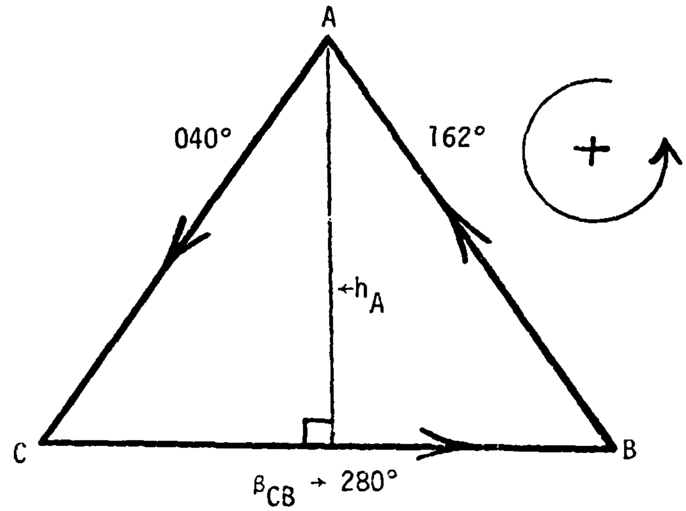
Vertical motion was computed in the layer from the surface to 850 mb level by dividing the convergence in that layer by the area of the triangle (see Table 2). It was assumed that any convergence in this layer must escape by passing vertically through the 850 mb level. It was assumed that the air would rise uniformly over the area.

$$VM_{SFC - 850} = Conv_{SFC - 850} + Conv\ 850\text{-}700) \div Area$$

Computation of the vertical component of vorticity was accomplished using the equation $\zeta = \zeta_A + \zeta_B + \zeta_C$ where ζ_A was the partial vertical component of the vorticity at one of the corners and was computed from the equation:

$$\zeta_A = - \frac{V_A}{h_A} \cos\ (\beta_{CB} - WD_A)$$

where V_A is the wind speed in m s^{-1} reported at point A, H_A is the height of the triangle with A at the apex and CB at the base. β_{CB} is the asmith of the leg of the triangle opposite point A. All asmiths were taken in a counterclockwise direction and counterclockwise vorticity was considered to be positive. WD_A is the reported wind direction at A. $- VA \cos\ (\beta_{CB} - WD_A)$ converts the reported wind to that component of the wind parallel to the opposite side of the triangle and insures the proper sign (see Fig. A3).



$$\zeta_A = -\frac{V_A}{h_A} \cos(\beta_{CB} - WD_A)$$

V_A = wind velocity at A

h_A = height of triangle

β_{CB} = orientation of CB

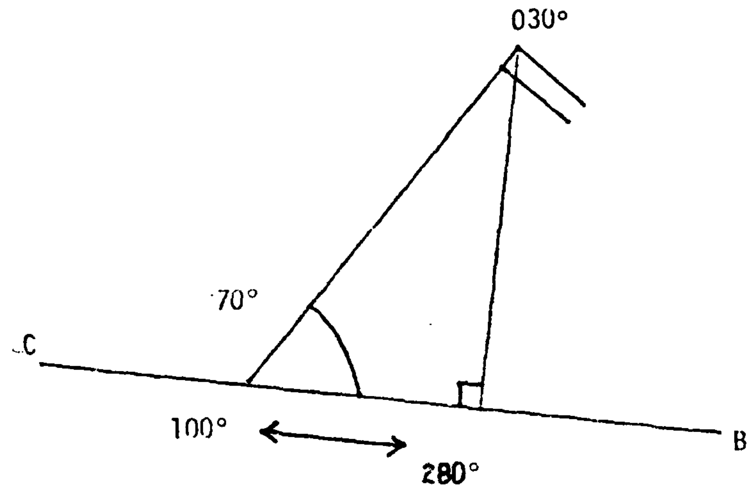
WD_A = wind direction at A

$$\zeta = \zeta_A + \zeta_B + \zeta_C$$

Fig. A3. Computation of the vertical component of relative vorticity using a modified Bellamy (1949) technique.

Ex: Wind at A 030/20

$\beta_{CB} = 280°$ $WD_A = 030°$ and $\beta_{CB} - WD_A = 250°$



The projection of the wind on the BC leg of the triangle would be -20 cos (70°). As cos 70° is positive the resultant vorticity value would be negative which is clearly incorrect. The CB azimuth is used to correct this sign error. Recall cos 70° = - cos 250°. The negative value of cos 250°, when multiplied with the negative of the wind speed in the equation yields the proper sign for vorticity.

Similarly the vertical component of vorticity was computed for points B and C. Adding the three values produced a vorticity value for the level. The vertical component of vorticity was computed for the 850, 700 and 500 mb levels.

Moisture advection in the triangle was computed by adding the moisture advection at each wall to the moisture advection at the top of the triangle volume. Moisture advection at each wall was computed using the following equation:

Moisture advection through one wall = volume of air through wall X average density for layer X average mixing ratio for the wall.

The volume data, calculated earlier in determining convergence, was multiplied by an average density to give the mass transport through each wall.

Average density values were developed for each layer. A value of 1.1 Kg m^{-3} was used for the surface to 850 mb layer, 0.96 Kg m^{-3} was used for the 850-700 mb layer, 0.77 Kg m^{-3} was used for the 700-500 mb layer and 0.70 Kg m^{-7} was used for the volume at 500 mb. Computing the average mixing ratio for each wall involved several steps as the moisture at each level was expressed as relative humidity. First saturation vapor press (e_s) was calculated for each point using the following equation:

$$e_s = 6.11 \times 10^{\frac{7.5t}{237.2 + t}}$$

where t is in C°.

Vapor pressure was calculated using:

$$e = \frac{RH \times e_s}{100}$$

where RH is the relative humidity at each point.

In 1979 and 1980 relative humidity values were not available and were computed using the equation:

$$RH = \frac{e}{e_s} = \frac{6.11 \times 10^{\left(\frac{(a)(t_d)}{b+t_d}\right)}}{6.11 \times 10^{\left(\frac{(a)(t)}{b+t}\right)}}$$

where a is a constant 7.5, and b is a constant 237.2. The dewpoint depression is t_d and t is the temperature in C°. The mixing ratio (w) was then computed using:

$$w = \frac{622\ e}{p - e_s}$$

where p is pressure expressed in millibars. An average mixing ratio was then obtained for each wall using the same procedure described earlier for obtaining an average wind component for each wall.

Moisture advection through the top of the triangular volume was determined by multiplying the average mixing ratio at 500 mb, an average density at 500 mb (0.70 Kg m^{-3}), and the net convergence of the three layers.

$$\text{H2OTOP} = \text{w500} \times 0.7 \times \text{net convergence}$$

The surface to 850 mb moisture advection between Del Rio and Victoria (DVH2O) was used as a separate element in the analysis.

VITA

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He obtained a Bachelor of Science degree in Meteorology in 1969 from the University of Utah. He earned an associate degree in Biology from Belleville Area College of Illinois in 1975 and a Master of Business Administration degree from Webster College of St. Louis, Missouri in 1976. He earned a Master of Science degree in Meteorology from Texas A&M University in 1982. He was elected to membership in the University of Utah chapter of Chi Epsilon Pi, the national meteorology honor society in 1968, and served as the 1981-82 president of the Texas A&M University chapter. He was elected to Sigma Gamma Epsilon, the national honorary society for the earth sciences, in 1982.

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